

## **North Pacific Acoustic Laboratory: Scripps Institution of Oceanography**

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## **LONG-TERM GOALS**

The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

## **OBJECTIVES**

Long-range, deep-water acoustic propagation experiments conducted in the North Pacific Ocean over the last twenty years (Worcester and Spindel, 2005) have used controlled sources and vertical and horizontal line array receivers to explore the range and frequency dependence of the fluctuation statistics and coherence (vertical, horizontal, temporal) of resolved ray and mode arrivals and of the highly scattered finale first observed in the SLICE89 experiment (Worcester et al., 1994). The most

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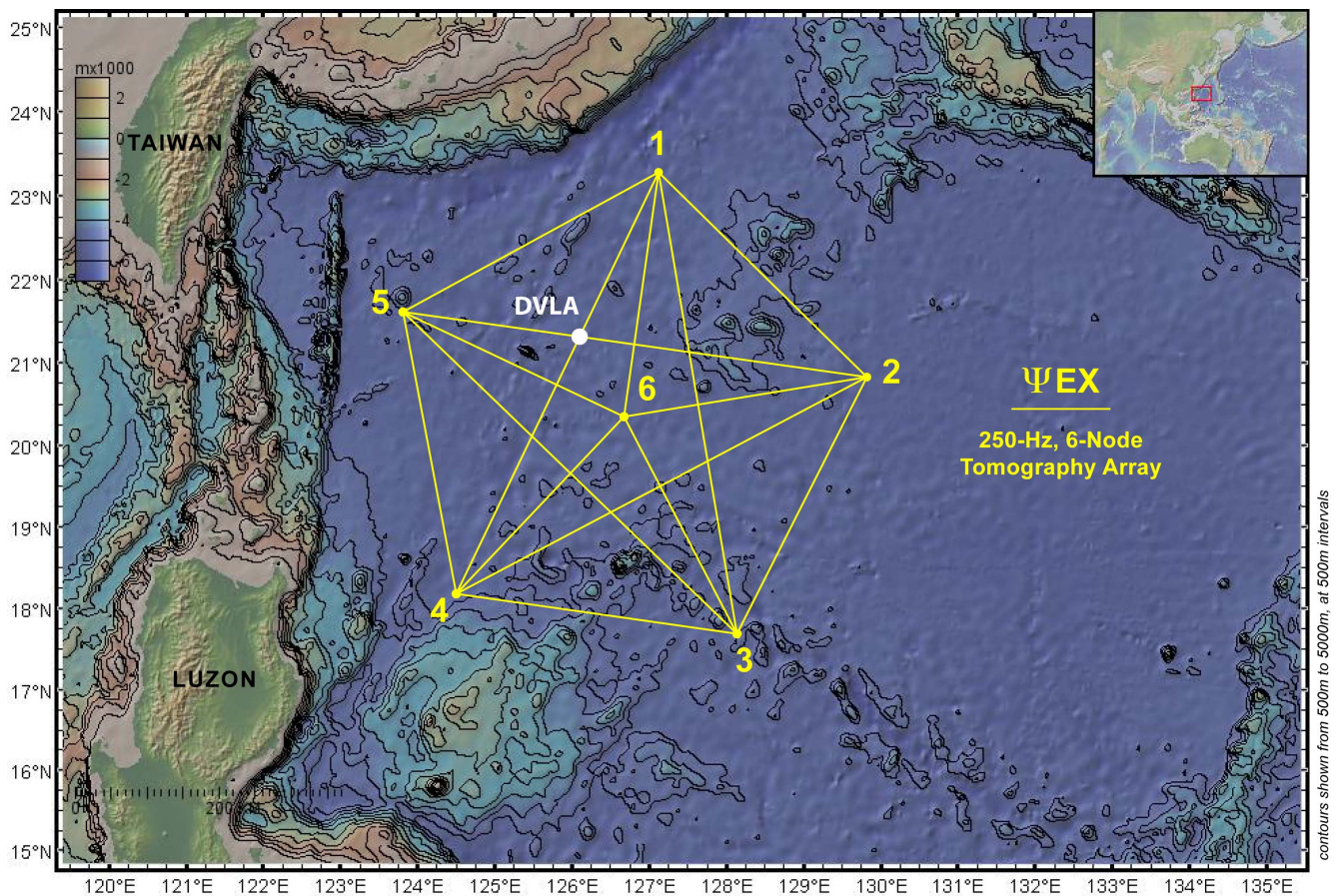
recent experiment, which was conducted in 2004–2005, employed a deep vertical line array (VLA) receiver spanning the surface conjugate depth specifically to determine the vertical structure of the acoustic energy that had previously been observed on bottom-mounted receivers several hundred meters into the geometric shadow zones below cusps (caustics) of the acoustic timefronts (Dushaw et al., 1999).

These experiments reflect the background sound-speed field, the relatively low level of eddy variability, the small-scale sound-speed fluctuations caused by internal tides, internal waves, and density-compensated temperature and salinity variations (spice), and the noise sources found in the relatively benign northeast and north central Pacific Ocean. We are now preparing to conduct the next experiment in the series in the complex and highly dynamic northern Philippine Sea during 2010–2011, preceded by a short Pilot Study/Engineering Test in April–May 2009. The objectives are to (i) understand the impacts of fronts, eddies, and internal tides on acoustic propagation in this highly variable region, (ii) determine whether acoustic methods, together with satellite, glider and other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improve our understanding of the basic physics of scattering by small-scale oceanographic variability due to internal waves and spice, and (iv) characterize the ambient noise field, particularly its variation over the year and its depth dependence.

## **APPROACH**

A new, water-column-spanning Distributed Vertical Line Array (DVLA) receiver will be embedded within an ocean acoustic tomography array for the 2010–2011 Philippine Sea Experiment (Fig. 1). Transmissions from the tomographic sources to the DVLA will be used to study acoustic propagation and scattering in this strongly range-dependent, deep-water region. The tomographic measurements, when combined with satellite and other in situ measurements and with ocean models, will help characterize the baroclinic and barotropic structure of the rapidly varying environment in the northern Philippine Sea, providing an eddy-resolving, 4-D sound-speed field for use in making acoustic predictions. Our efforts in both the 2009 Pilot Study/Engineering Test and the 2010–2011 Philippine Sea Experiment are closely coordinated with the efforts of A. Baggeroer (MIT), G. D'Spain (MPL-SIO), and J. Mercer (APL-UW).

The new DVLA will allow both modal and ray-based analyses of the propagation. The acoustic propagation experiments that have been conducted in recent years have been constrained by the lack of vertical line array receivers capable of spanning the full water column in deep water. Although such arrays are required to enable the separation of high-order acoustic modes using spatial filtering and to fully characterize the acoustic timefronts found in deep water propagation, to our knowledge a fully water-column-spanning array has never been deployed in deep water. We have developed a novel approach using distributed, self-recording hydrophones with timing and scheduling provided by a small number of specially modified versions of our Simple Tomographic Acoustic Receiver (STAR) data acquisition system and controller, called D-STARs. The enabling technologies for this approach are (i) the availability of flash memory modules that can store several gigabytes of data and be located in a small pressure case at each hydrophone, making it unnecessary to transfer acoustic data from the hydrophone to the central controller for storage, and (ii) inductive modems that allow low-bandwidth communication for command, control, and time synchronization between the D-STAR controllers and the Hydrophone Modules over standard 3 x 19 jacketed oceanographic mooring wire.



**Figure 1. Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of five 250-Hz acoustic transceivers arranged in a pentagon with a sixth transceiver in the center (T1, T2, ... T6) and a new DVLA receiver. The array radius is 330 km.**

## WORK COMPLETED

*Shadow-zone arrivals.* L. Van Uffelen, who is supported by an ONR Graduate Traineeship, has taken the lead in examining the shadow-zone arrivals seen in the 250-Hz receptions on the Shallow and Deep VLA receivers in the SPICEX component of the 2004–2005 NPAL experiment. She has compared the measured shadow-zone arrivals with parabolic equation (PE) simulations for sound-speed fields with and without significant internal-wave variability. A manuscript describing her results has been submitted to the *Journal of the Acoustical Society of America* (Van Uffelen et al., 2008).

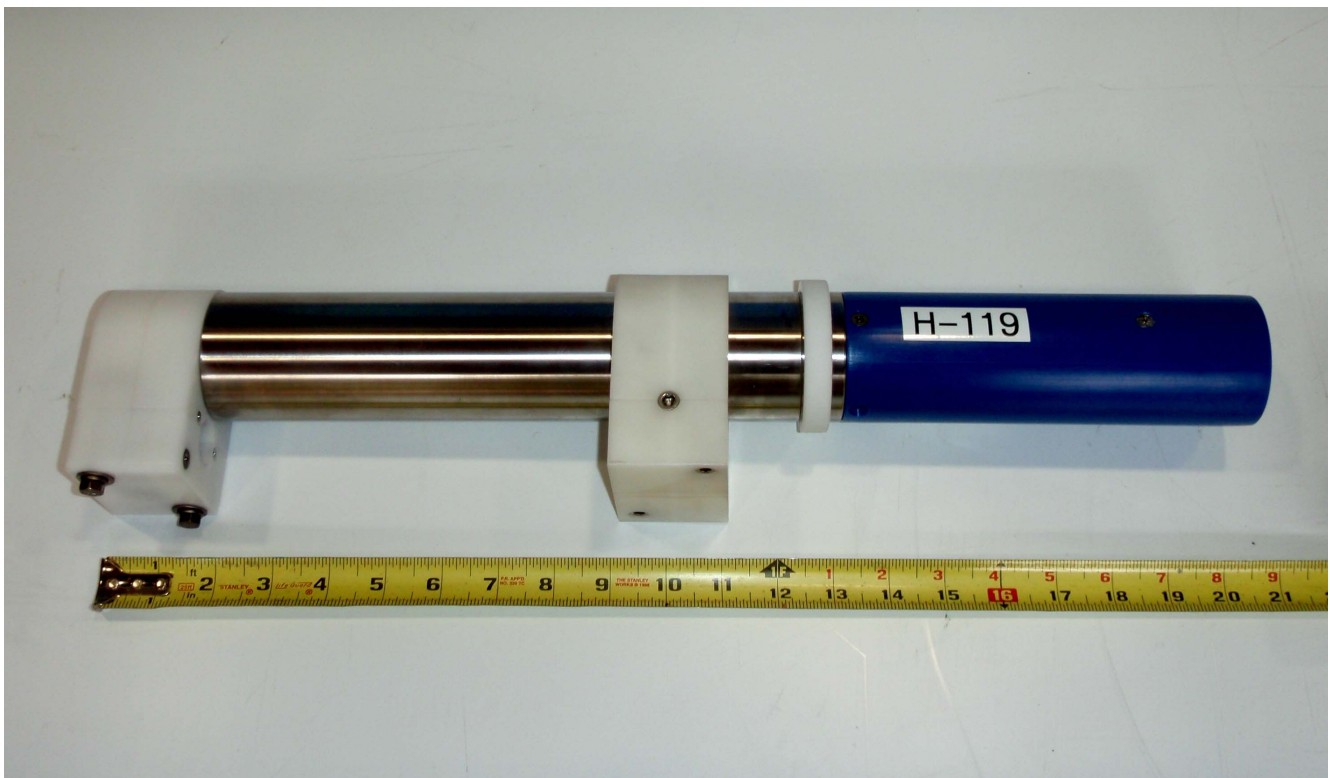
*Acoustic Thermometry.* We continued analysis of the nearly decade-long time series of acoustic measurements of large-scale, depth-averaged temperature in the North Pacific Ocean obtained by the Acoustic Thermometry of Ocean Climate (ATOC) and NPAL projects, working closely with B. Dushaw (APL-UW). The measured travel times were compared with travel times derived from four independent estimates of the North Pacific: (i) climatology, as represented by the World Ocean Atlas 2005 (WOA05), (ii) objective maps of the upper ocean temperature field derived from satellite altimetry and in situ profiles, (iii) an analysis provided by the Estimating the Circulation and Climate of the Ocean project as implemented at the Jet Propulsion Laboratory (JPL-ECCO), and (iv) simulation results from a high-resolution configuration of the Parallel Ocean Program (POP) model. Modern



ocean general circulation models have the vertical resolution needed for acoustic propagation calculations, allowing straightforward comparison of measured and predicted travel times as a first step in using the acoustic data to constrain the models. A manuscript describing the results has been submitted to the *Journal of Geophysical Research* (Dushaw et al., 2008).

*Philippine Sea Experiment.* Engineering efforts have focused on the development of the new DVLA receiver. The DVLA will be modular, made up of subarrays, each of which has one D-STAR controller and approximately 30 distributed, internally-recording Hydrophone Modules (Fig. 2). Each D-STAR provides timing and scheduling to the Hydrophone Modules in its subarray via inductive modems over standard mooring wire. The nominal length of each subarray is 1000 m, although shorter subarrays can be easily fabricated. (The length of wire rope that can be conveniently handled on deck sets the maximum overall subarray length at about 1000 m.) The Hydrophone Modules will be clamped to the wire rope at the time of deployment, making the DVLA readily configurable for different experiments. The wire rope jacket will have extruded helical strakes in order to reduce mooring strum. The maximum operating depth is 6000 m.

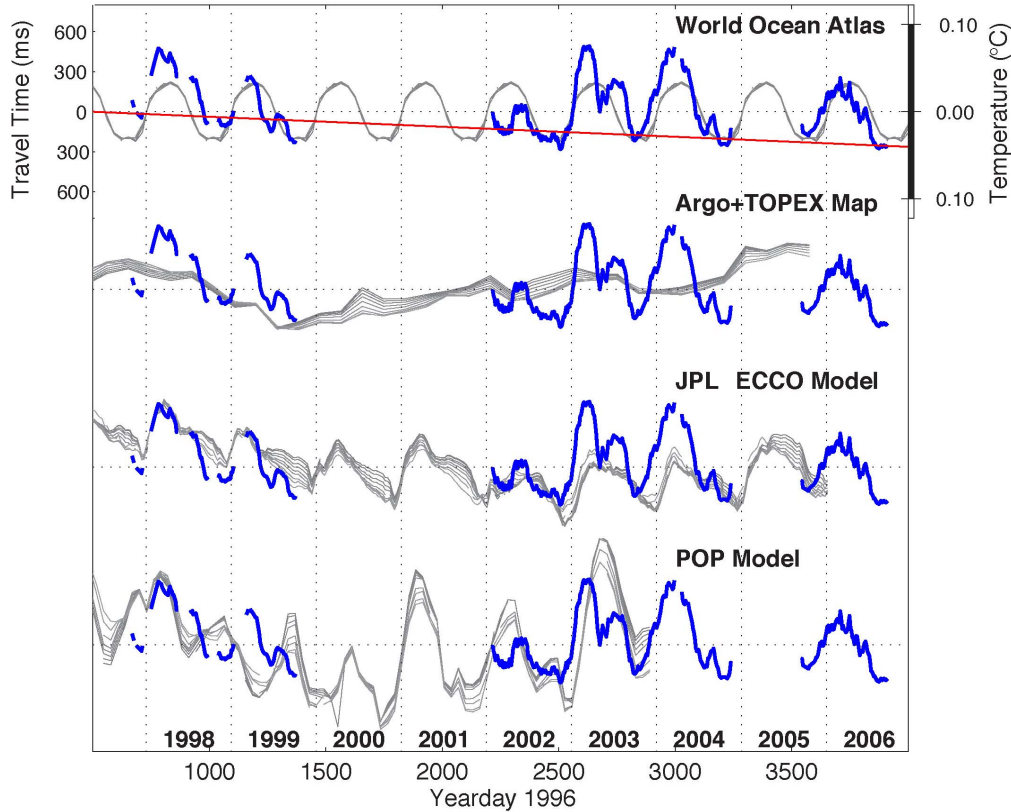
The timing between D-STARs will be synchronized acoustically. A long-baseline acoustic navigation system will measure the position and shape of the DVLA. The entire system is autonomous, with up to approximately a 5% duty cycle for one year.



**Figure 2. Prototype Hydrophone Module to be used in the DVLA receiver, consisting of a titanium pressure case and an HTI-90-U hydrophone in a polyethelene sleeve. Each Hydrophone Module includes a precision temperature sensor in order to allow calculation of the sound-speed profile at the DVLA.**

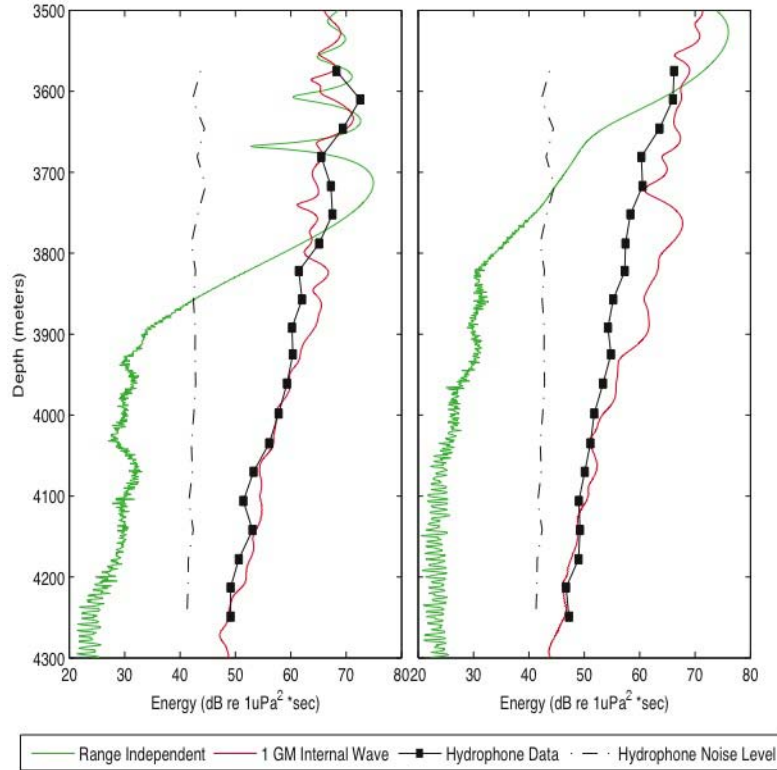
## RESULTS

**Acoustic Thermometry.** Large-scale temperatures in the North Pacific Ocean were measured by long-range acoustic transmissions over the decade 1996–2006. Acoustic sources located off central California (1996–1999) and north of Kauai (1996–1999, 2002–2006) transmitted to receivers distributed throughout the northeast and north central Pacific. The acoustic travel times are inherently spatially integrating, which suppresses mesoscale variability and provides a precise measure of range- and depth-averaged temperature. The interannual, seasonal, and shorter period variability is large, with substantial changes sometimes occurring in only a few weeks. Linear trends estimated over the decade are small compared to the interannual variability and inconsistent from path to path, with some acoustic paths warming slightly and others cooling slightly. The measured travel times were compared with travel times derived from four independent estimates of the North Pacific (Fig. 3). The comparisons provide a stringent test of the large-scale temperature variability in the models. The differences are sometimes substantial, indicating that acoustic thermometry data can provide significant additional constraints for numerical ocean models. In particular, the acoustic data show that WOA05 is a better estimate of the time-mean hydrography than either the JPL-ECCO or the POP estimates, both of which proved incapable of reproducing the observed acoustic arrival patterns.



**Figure 3.** Comparison of measured travel times for transmissions from the Kauai source to receiver *k* at a range of approximately 3500 km (blue) with travel times calculated using sound-speed fields derived from the World Ocean Atlas 2005, objective maps combining in situ temperature profiles and sea surface height from satellite altimetry (Argo+TOPEX Map), the JPL-ECCO model, and the POP model (gray). For comparison, the trend in travel time corresponding to a 5 m°C/year change in temperature at the sound-channel axis is also shown (red).

*Shadow-zone arrivals.* Acoustic data from two VLA receivers deployed in close proximity in the North Pacific Ocean during the 2004–2005 NPAL experiment, together virtually spanning the water column, show the vertical structure of the shadow-zone arrivals for transmissions from broadband 250-Hz sources moored at the sound channel axis (750 m) and slightly above the surface conjugate depth (3000 m) at ranges of 500 and 1000 km. Comparisons to parabolic equation simulations for sound-speed fields that do not include significant internal-wave variability show that early branches of the measured timefronts consistently penetrate as much as 500–800 meters deeper into the water column than predicted (Fig. 4). Subsequent parabolic equation simulations incorporating sound-speed fluctuations consistent with the Garrett-Munk internal-wave spectrum at full strength accurately predict the observed energy level to within 3–4 dB rms over the depth range of the shadow-zone arrivals.



**Fig. 4. Measured and predicted energy in the pair of lower cusps occurring after 675 seconds for the S2 HLF-5 to DVLA propagation path at 1000-km range. Energy was calculated for a time window of 675.0 to 675.2 seconds for the first cusp (left) and 675.2 to 675.4 seconds for the second cusp (right). Hydrophone data and noise levels are shown for the 20 phones on the lower segment of the DVLA.**

*Ambient noise.* Farrell and Munk (2008) find a minimum acoustic noise level of about 50 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  on the deep-sea bottom at about 20 Hz. This is the spectral intensity of the deep pressure spectrum associated with oppositely traveling short surface gravity waves modified by surface tension. Except for occasional biological noises, this probably constitutes a limit to the detection of acoustic signals in the ocean column.

## IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior. The data indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

## TRANSITIONS

*Simple Tomographic Acoustic Receiver (STAR)*. The Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, is funded in the framework of the European Union DAMOCLES and ACOBAR projects to develop an ocean acoustic tomography system for monitoring the average heat content across Fram Strait at 78°50'N. After reviewing various possible approaches to developing an ocean acoustic tomography system, NERSC purchased two STARs from my group and a swept-frequency acoustic source (190–290 Hz) from Webb Research Corporation, which in turn ordered a third STAR from us to serve as the controller for the source. This tomographic system was successfully deployed during August 2008 on the eastern side of Fram Strait. NERSC has funding to purchase two additional swept-frequency sources. We anticipate providing the required STAR controllers for these sources. The STARs will be configured to serve as receivers as well, forming acoustic transceivers. The source and receivers now in the water will be recovered during summer 2009 and redeployed shortly thereafter, together with the two new transceivers.

## RELATED PROJECTS

A large number of investigators and their students are currently involved in ONR-supported research related to the NPAL project. The Principal Investigators include R. Andrew (APL-UW), A. Baggeroer (MIT), F. J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), B. Dushaw (APL-UW), O. Godin (NOAA/ETL), N. Grigorieva (St. Petersburg State Marine Technical Univ.), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (Univ. Hawaii), J. Mercer (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), D. Rudnick (SIO), E. Skarsoulis (IACM/FORTH), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), and M. Wolfson (APL-UW).

## REFERENCES

Dushaw, B. D., B. M. Howe, J. A. Mercer, R. C. Spindel, and The ATOC Group (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. A. Dzieciuch, A. M. G. Forbes, B. M. Howe, D. Menemenlis, J. A. Mercer, K. Metzger, W. H. Munk, R. C. Spindel, P. F. Worcester, and C. Wunsch) (1999), Multimegahertz-range acoustic data obtained by bottom-mounted hydrophone arrays for measurement of ocean temperature, *IEEE J. Ocean. Eng.*, 24, 202-214.

Dushaw, B. D., P. F. Worcester, W. H. Munk, R. C. Spindel, J. A. Mercer, B. M. Howe, K. Metzger, Jr., T. G. Birdsall, R. K. Andrew, M. A. Dzieciuch, B. D. Cornuelle, and D. Menemenlis (2008), A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.* [submitted]

Farrell, W. E. and W. Munk (2008), What do deep-sea pressure fluctuations tell about short surface waves?, *Geophys. Res. Lett.*



Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, and D. L. Rudnick (2008), The vertical structure of shadow-zone arrivals at long range in the ocean, *J. Acoust. Soc. Am.* [submitted]

Worcester, P. F., and R. C. Spindel (2005), North Pacific Acoustic Laboratory, *J. Acoust. Soc. Am.*, *117*(3), 1499-1510.

Worcester, P. F., B. D. Cornuelle, J. A. Hildebrand, W. S. Hodgkiss, T. F. Duda, J. Boyd, B. M. Howe, J. A. Mercer, and R. C. Spindel (1994), A comparison of measured and predicted broadband acoustic arrival patterns in travel time-depth coordinates at 1000-km range, *J. Acoust. Soc. Am.*, *95*, 3118-3128.

## PUBLICATIONS

Dushaw, B. D., P. F. Worcester, W. H. Munk, R. C. Spindel, J. A. Mercer, B. M. Howe, K. Metzger, Jr., T. G. Birdsall, R. K. Andrew, M. A. Dzieciuch, B. D. Cornuelle, and D. Menemenlis (2008), A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.*

Farrell, W. E. and W. Munk (2008), What do deep-sea pressure fluctuations tell about short surface waves?, *Geophys. Res. Lett.*

Raghukumar, K., B. D. Cornuelle, W. S. Hodgkiss, and W. A. Kuperman (2008), Pressure sensitivity kernels applied to time-reversal acoustics. *J. Acoust. Soc. Am.*, **124**, 98–112. [published, refereed]

Sagen, H., S. Sandven, E. Skarsoulis, G. Piperakis, M. Kalogerakis, and P. F. Worcester (2007), DAMOCLES: The Fram Strait acoustic tomography system, in *Second International Conference on Underwater Acoustic Measurements*, edited, Foundation for Research and Technology - HELLAS, Heraklion, Crete, 1171–1176. [published, from in press]

Song, H.-C. and M. A. Dzieciuch (2008), Feasibility of global-scale synthetic aperture communications, *J. Acoust. Soc. Am.*

Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, and D. L. Rudnick (2008), The vertical structure of shadow-zone arrivals at long range in the ocean, *J. Acoust. Soc. Am.*